CHAPTER III

FEASIBILITY OF CROSSED-BEAM APPLICATIONS TO COMBUSTIVE FLOWS

by

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SUMMARY

Group velocities of local areas of combustion in a turbulent flame have been optically measured by employing the crossed-beam correlation technique. Identification of velocity and photo-chemical reactions through correlation of emission fluctuations is discussed.

III-1. INTRODUCTION

The feasibility of applying the cross-beam technique was first developed by Fisher and Krause [III-1] in a subsonic jet. The method was extended to measure atmospheric wind speeds by Stephens, Sandborn and Montgomery [III-2] and later to measure optical fluctuations in a glow discharge described in Chapter II by Stephens and Thomison. The glow discharge measurements studied fluctuations of emission processes rather than extinction processes. Earlier tests depended on fluctuations in the transmission of an independent light source produced by changes in the optical density of a gas. These changes in optical density correspond to like changes in the mass density of the gas. The source for the wind tunnel measurements was artificial light, while that for the atmospheric tests was scattered sunlight. The tests described in this paper use the light emitted from a turbulent flame to study the combustion process of the flame itself. No outside light source is used. These tests demonstrate the feasibility of using the cross-beam technique to successfully retrieve velocity and spectroscopic information from a combustion process.

III-2. PHOTOGRAPHIC EVALUATION OF FLAME PROPAGATION

Optical fluctuations in the body of a turbulent flame are due to turbulent eddies of burned and unburned gases (see Fig. III.1). These turbulent eddies may be defined as blobs of fluid which experience a coherent change of emissivity. In general, these blobs have a random velocity and after traveling a mixing length equal, on the average, to their diameter, they lose their separate identities [III-3].

Before the actual cross-beam flame tests, the flame was photographed with a high-speed movie camera to determine the type of fluctuations present. The best visualizations of the flame motion were obtained at camera speeds in excess of 1000 frames per second. The movies were used primarily to determine the best position along the axis of the flame to observe with cross-beam photo-detectors. Qualitative velocity measurements are illustrated by the consecutive eight frames shown in Figure III.1. The formation and motion of an emitting blob of fluid are observed at the right edge of the figure. The blob is moving to the right with a speed of approximately 5.0 m/sec and its axial scale is approximately 60 mm.

III-3. CROSS-BEAM EXPERIMENTS

Two mutually perpendicular lines of sight were set to select the local point of investigation in the flame. All zero separation measurements refer to the selected position 10.1 cm downstream from the nozzle exit. To achieve separation measurements, the horizontal photo-multiplier beam remained fixed, while the vertical beam was moved downstream as in Figure III.2. The focal length of the optics was 11.3 cm with a beam diameter at an intersection of approximately 2 mm. The measurements were made primarily at 5250 Å.

A flame was achieved by feeding C_2H_2 and O_2 to the nozzle, with an oxygen-to-fuel ratio of 0.92. This ratio was set by adjusting the pressure controls of the feeder lines to 3 psig for C_2H_2 and 1 psig for O_2. The actual oxygen and fuel mass flow ratio, calculated from the pressures assuming sonic speed at the nozzle exit, were 67.2 g/sec and 62.7 g/sec, respectively. The oxygen-to-fuel ratio was insufficient for complete combustion, and most of the burning occurred at the flame boundaries where ambient air was entrained.

The actual experiments were made by feeding the outputs of the photo-multipliers directly into the PAR analog correlator to obtain a covariance reading. This on-line analog computer assumes that no D.C. shifts, trends, or gain instabilities were introduced by the electronics.

Further, the covariance thus obtained will become uncertain as soon as the correlation coefficient (correlation/mean signal power) drops below 10 percent.

Within the above assumptions, the analog computations of the PAR correlator should form an estimate of the temporal covariance function, which is defined as follows.

$$C_{xy}(\tau;\xi;\lambda;\ \ldots) = \langle i_x i_y \rangle$$

$$= \frac{1}{T} \int_0^T i_x(t;\lambda)\ i_y(t-\tau;\lambda)\ dt, \qquad (1)$$

where

$i_x(t)$ - instantaneous fluctuations of intensity from the undelayed channel

$i_y(t-\tau)$ - instantaneous fluctuations from the delayed channel

τ - delay time set during data reduction

t - real time

T - total integration time.

This covariance should be related to the statistics of local emission fluctuations. Let $\ell = \eta$ or $\ell = \zeta$ denote a point on one of the two beams. The emission fluctuations in the beam element $\Delta\ell$ around this point are then described by the emission coefficient fluctuations

$$K'(\ell;\ t;\ \lambda) = \frac{\Delta I'_e(\ell;\lambda;t)}{\Delta\ell\ I(\ell;\lambda;t)}\ , \qquad (2)$$

where

$I(\ell;\ \ldots)$ - radiative power flux through beam cross section at ℓ

$\Delta I'_e$ - emission fluctuation in beam element $\Delta\ell$.

Crossed-beam theory [III-4] now indicates that the normalization of the A.C.-coupled signals with the D.C. mean values should provide a covariance estimate, which is equal to the point-area product mean value of the emission coefficient fluctuations K' around the beam intersection, $\vec{x}$.

$$G(\xi;\tau;\lambda)_{\vec{x}} = \frac{< i_x i_y >}{\bar{I}_x \bar{I}_y} =$$

$$= <K'(\vec{x},t;\lambda) \underset{\substack{\text{eddy} \\ \text{correction}}}{\int\int} K'(\vec{x}+\vec{\xi};\ t-\tau;\lambda)\ d\eta d\zeta > , \qquad (3)$$

where

$\bar{I}_x$ = average D.C. intensity from beam x

$\bar{I}_y$ = average D.C. intensity from beam y

ξ = axial separation distance

$\vec{\xi}$ = (ξ,η,ζ) point coordinates in beam fixed frame.

The last equation demonstrates that local emission variations in a flame can be retrieved by crossed-beam correlative techniques. The following pilot experiments were conducted to experimentally check this theoretical claim.

III-4. VELOCITY MEASUREMENTS AND DETERMINATION OF COMBUSTION EFFECTS

To obtain a velocity measurement in the flame, the two photo-multiplier beams were separated along the flame axis, and the peak cross-correlation of these fluctuations revealed the average transit time for a turbulent blob. This transit time yielded the average velocity of the blobs over that distance. The results are illustrated in Figure III.3. They show a decreasing velocity with an increase in the downstream beam separation. The speed of the eddy that was indicated by the noise falls into the speed interval shown in Figure III.3. All photo-multiplier

records taken from single photo-multiplier time histories show a broad band power spectrum (see Chapter II). The signals could easily be resolved out of the photo-multiplier and flow noise, as apparent from the large values of the correlation coefficient for a zero beam separation. The values were at least 20 percent, while some even exceeded 50 percent (see table III.1). Further, the correlation curves were consistent and stable with repeating runs. When the separation was increased to 3.8 cm, the value of the correlation coefficient dropped below 10 percent, and no usable measurements were obtained.

Additional tests were made to separate photo-chemical emission from heat radiation by studying the change of the cross-correlation as a function of optical wave length [III-4]. All these measurements were taken with intersecting beams.

The results of this experiment showed distinct correlation peaks when changing the optical wave length. This would not have been produced by heat radiation. Some of these emission peaks are centered close to optical wave lengths that correspond to known emission bounds for a C_2H_2 - O_2 flame [III-5]. These results are illustrated in Figure III.4. This coincidence of the peak positions in crossed-beam spectra and published mean value emission spectra gives additional confirmation to the claim that local emission variations have been retrieved.

III-5. CONCLUSIONS AND RECOMMENDATIONS

This research has demonstrated the feasibility of the use of the cross-beam correlation technique to successfully retrieve both velocity and spectroscopic information from a combustion. The next logical step would be to attempt similar studies in an actual rocket plume.

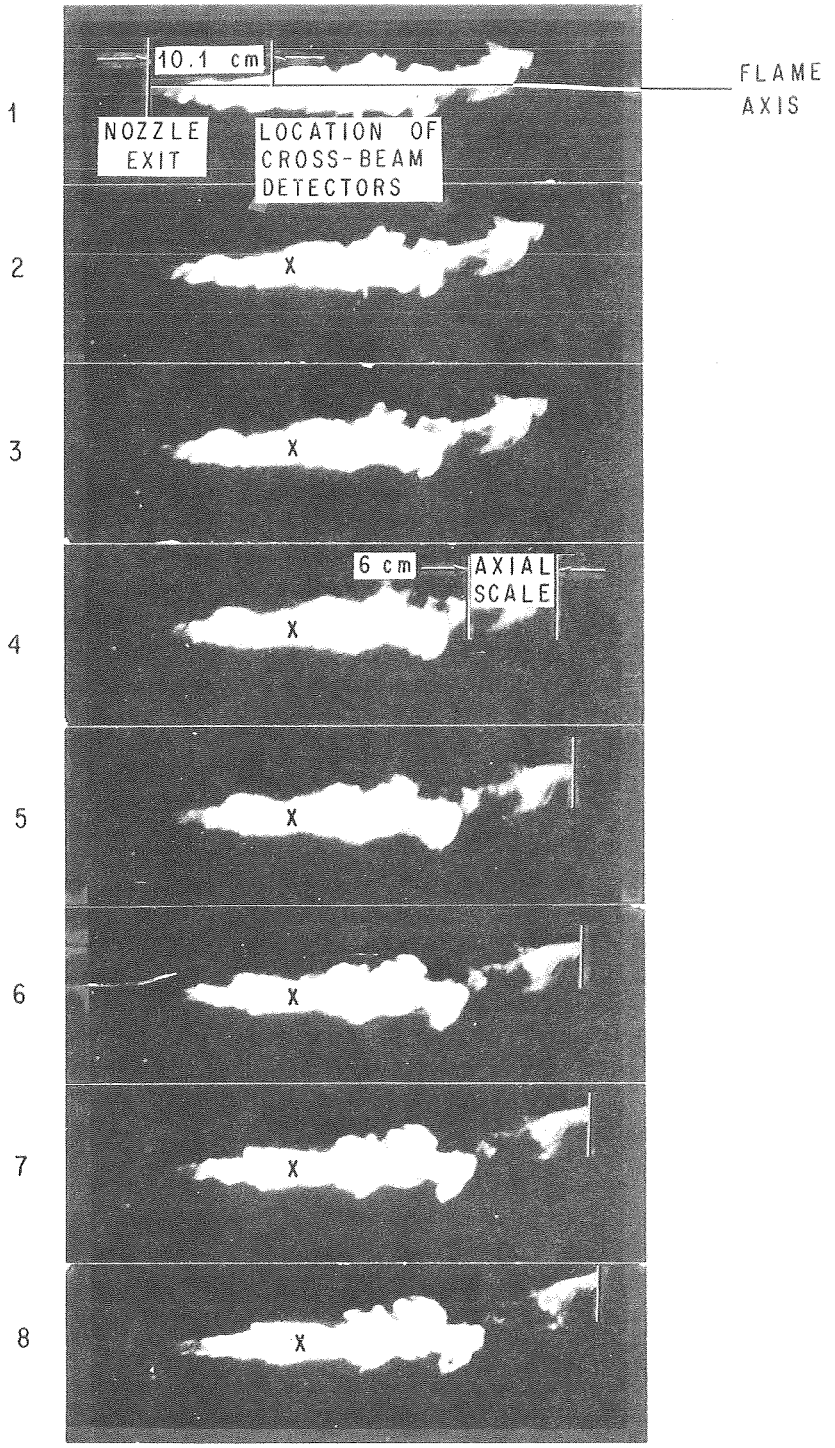

FIGURE III.1. TURBULENT BLOB PROPAGATION IN A C_2H_2 - O_2 FLAME, 500 FRAMES/SEC

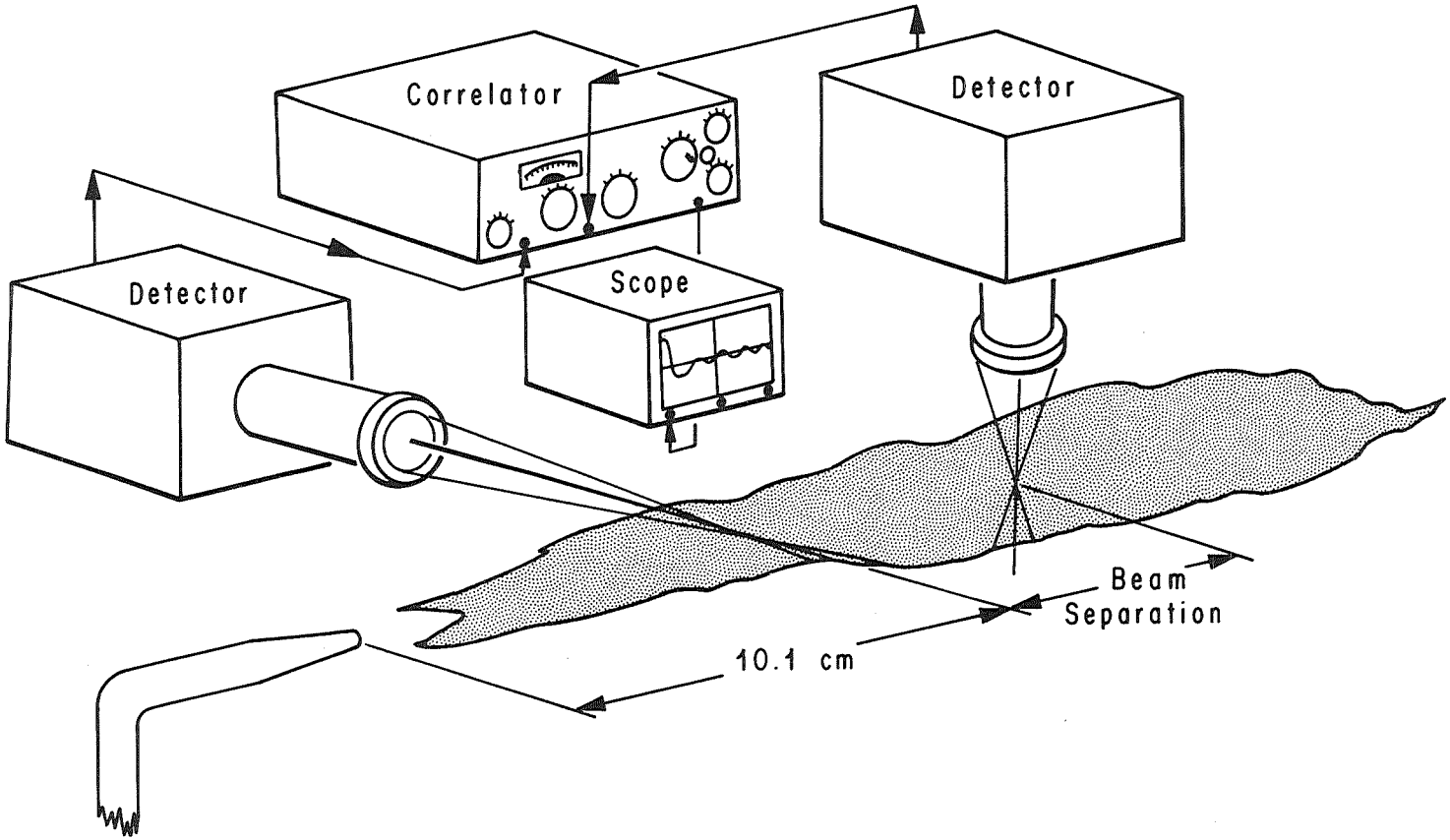

FIGURE III.2. EXPERIMENTAL SETUP

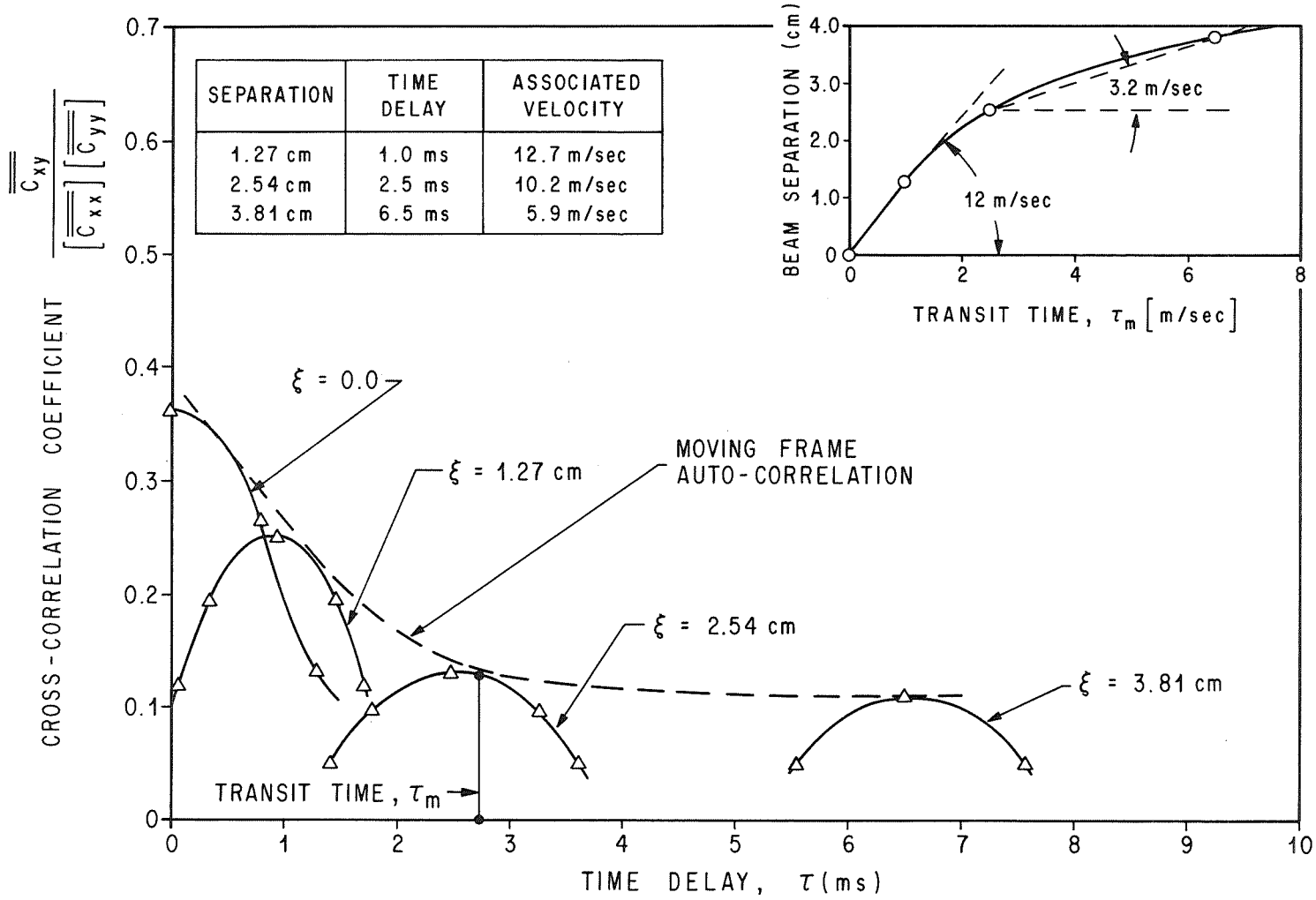

FIGURE III.3. VELOCITY CORRELATIONS

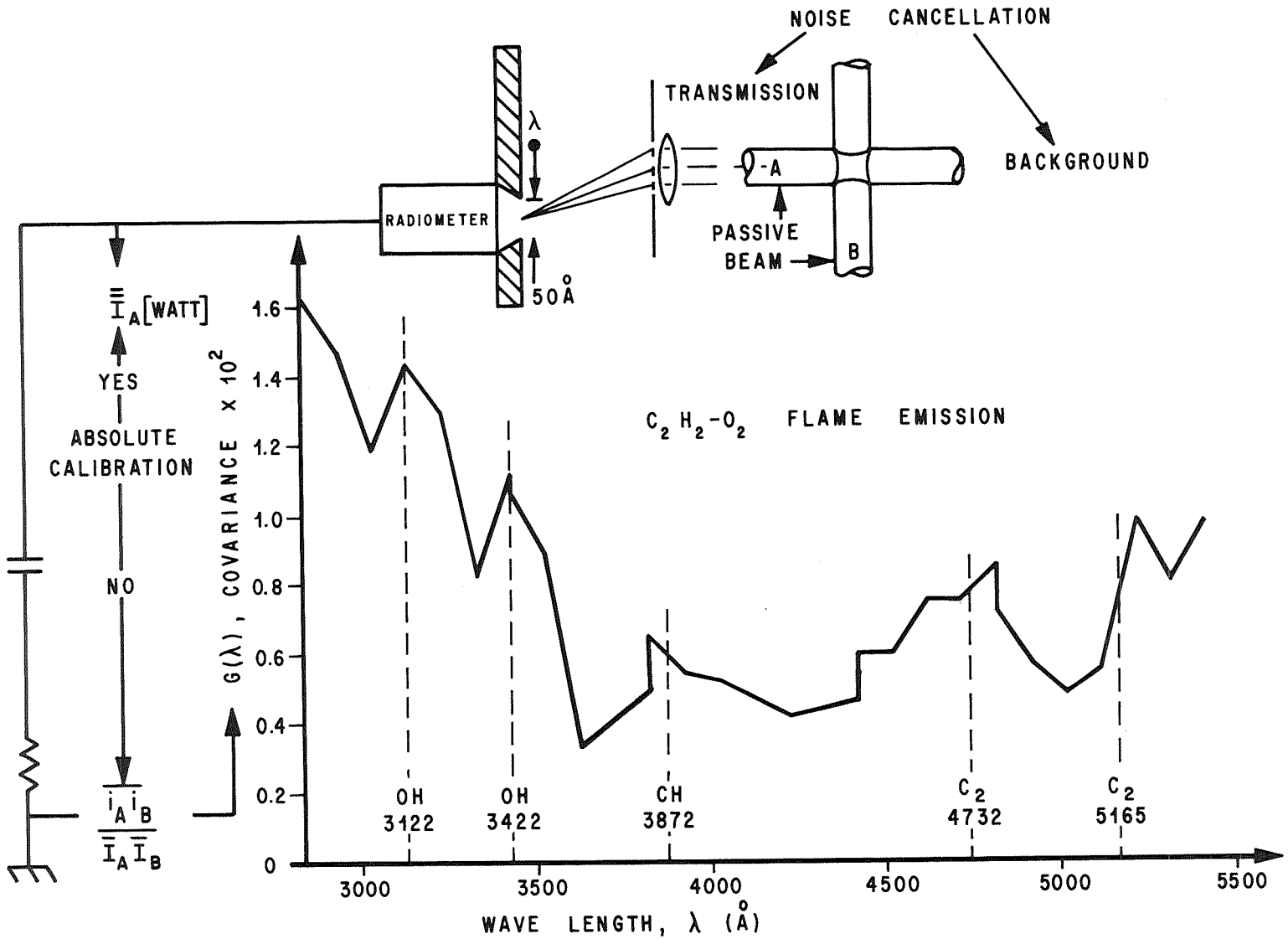

FIGURE III.4. PHOTO-CHEMICAL EMISSION IN A C_2H_2 - O_2 FLAME

TABLE III.1. DATA FOR OBSERVED PHOTO-CHEMICAL EMISSION IN A C_2H_2 - O_2 FLAME

λ WAVE LENGTH ANGSTROMS	$\frac{\overline{C_{xy}(0)}}{\sqrt{\overline{C_{xx}(0)}\ \overline{C_{yy}(0)}}}$ CORRELATION COEFFICIENT	$G(\lambda)_{\xi = \tau = 0}$ EMISSION COEFFICIENT
2850.0	0.238	0.0163
2950.0	0.257	0.0148
3050.0	0.261	0.0119
3150.0	0.262	0.0144
3250.0	0.246	0.0130
3350.0	0.280	0.0082
3450.0	0.335	0.0112
3450.0	0.315	0.0106
3550.0	0.303	0.0089
3650.0	0.191	0.0033
3750.0	0.201	0.0041
3850.0	0.331	0.0065
3850.0	0.344	0.0049
3950.0	0.302	0.0054
4050.0	0.338	0.0052
4150.0	0.322	0.0047
4250.0	0.350	0.0042
4350.0	0.334	0.0044
4450.0	0.350	0.0047
4450.0	0.381	0.0060
4450.0	0.402	0.0060
4650.0	0.442	0.0075
4750.0	0.408	0.0075
4850.0	0.396	0.0085
4850.0	0.387	0.0072
4950.0	0.366	0.0057
5050.0	0.341	0.0048
5150.0	0.391	0.0055
5250.0	0.492	0.0104
5250.0	0.506	0.0080
5350.0	0.331	0.0103
5450.0	0.223	0.0401
5500.0	0.156	0.0670

REFERENCES

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